

Homestake result, Sterile neutrinos and Low energy solar neutrino experiments

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Abstract

The Homestake result is about $\sim 2\sigma$ lower than the Ar -production rate, Q_{Ar} , predicted by the LMA MSW solution of the solar neutrino problem. Also there is no apparent upturn of the energy spectrum ($R \equiv N_{obs}/N_{SSM}$) at low energies in SNO and Super-Kamiokande. Both these facts can be explained if a light, $\Delta m_{01}^2 \sim (0.2-2) \cdot 10^{-5} \text{ eV}^2$, sterile neutrino exists which mixes very weakly with active neutrinos: $\sin^2 2\alpha \sim (10^{-5} - 10^{-3})$. We perform both the analytical and numerical study of the conversion effects in the system of two active neutrinos with the LMA parameters and one weakly mixed sterile neutrino. The presence of sterile neutrino leads to a dip in the survival probability in the intermediate energy range $E = (0.5 - 5) \text{ MeV}$ thus suppressing the Be , or/and pep , CNO as well as B electron neutrino fluxes. Apart from diminishing Q_{Ar} it leads to decrease of the Ge -production rate and may lead to decrease of the BOREXINO signal and CC/NC ratio at SNO. Future studies of the solar neutrinos by SNO, SK, BOREXINO and KamLAND as well as by the new low energy experiments will allow us to check this possibility. We present a general analysis of modifications of the LMA energy profile due to mixing with new neutrino states.

1 Introduction

In the assumption of CPT invariance the first KamLAND result [1] and the results of SNO salt phase [2] confirm the large mixing angle (LMA) MSW solution of the solar neutrino problem [3, 4, 5]. Is the LMA solution complete? If there are observations which may indicate some deviation from LMA?

According to the recent analysis, LMA MSW describes all the data very well [6, 7]: pulls of predictions from experimental results are below 1σ for all but the Homestake experiment [7]. The generic prediction of LMA for the Ar production rate is

$$Q_{Ar} = 2.9 - 3.1 \text{ SNU}, \quad (1)$$

which is about 2σ higher than the Homestake result [8]. This pull can be

- just a statistical fluctuation;
- some systematics which may be related to the claimed long term time variations of the Homestake signal [8];
- a consequence of higher fluxes predicted by the Standard Solar Model (SSM) [9] ¹,
- some physics beyond LMA.

Another generic prediction of LMA is the “upturn” of the energy spectrum at low energies (the upturn of ratio of the observed and the SSM predicted numbers of events). According to LMA, the survival probability should increase with decrease of energy below (6 - 8) MeV [5]. For the best fit point the upturn can be as large as 10 - 15 % between 8 and 5 MeV [10, 7]. Neither Super-Kamiokande (SK) [11] nor SNO [12] show the upturn, though the present sensitivity is not enough to make statistically significant statement.

There are also claims that the solar neutrino data have time variations with small periods [13]. If true, this can not be explained in the context of LMA solution.

Are these observations related? Do they indicate some new physics in the low energy part of the solar neutrino spectrum? In this paper we show that both the lower Ar -production rate and the absence of (or weaker) upturn of the spectrum can be explained by the effect of new (sterile) neutrino. The solar neutrino conversion in the non-trivial 3ν - context (when the effect of third neutrino is not reduced to the averaged oscillations) have been considered in a number of publications before [4, 14]. In particular, modification of the ν_e -survival probability due to the mixing with sterile neutrino has been studied [15]. Here we

¹For instance, the CNO -neutrino fluxes have rather large uncertainties. According to the SSM and in the LMA context they contribute to Q_{Ar} about 0.25 SNU, so that reduction of the CNO - fluxes by factor of 2 (which is within 2σ of the estimated uncertainties) leads to reduction of the Ar -production rate by $\Delta Q_{Ar} \sim 0.12$ SNU.

suggest specific parameters of the sterile neutrino which lead to appearance of a dip in the adiabatic edge of the survival probability “bath”, at $E = (0.5 - 2)$ MeV, and/or flattening of the spectrum distortion at higher energies $(2 - 8)$ MeV. The dip suppresses the Be - (ν_e) neutrino flux or/and other fluxes at the intermediate energies, and consequently, diminishes the Ar -production rate. It also diminishes or eliminates completely (depending on mixing angle and Δm_{01}^2) the upturn of spectrum. We comment on a possibility to induce time variations of signals by the presence of very small mixing with sterile neutrinos.

The paper is organized as follows. In the Sec. 2 we introduce mixing with sterile neutrino and study in sec. 3 both analytically and numerically the conversion as well as the energy profile of the effect. In Sec. 4 physical consequences of the modification of the energy profile are considered. We calculate predictions for observables, the Ar -production rate, the Ge -production rate, the CC/NC ratio at SNO and the rate at BOREXINO, as functions of the mixing and mass of sterile neutrino in sec. 5. We consider an impact of the sterile neutrino on the global fit of the solar neutrino data in sec. 6, where we describe three possible scenario in sec. 6. In sec. 7 we discuss future checks of the suggested scenarios. We present a general analysis of possible modifications of the LMA profile by mixing with additional neutrino states in the Appendix. Our results are summarized in sec. 8.

2 Sterile neutrino mixing and level crossing

Let us consider the system of two active neutrinos, ν_e and ν_a , and one sterile neutrino, ν_s , which mix in the mass eigenstates ν_1 , ν_2 and ν_0 :

$$\begin{aligned}\nu_0 &= \cos \alpha \nu_s + \sin \alpha (\cos \theta \nu_e - \sin \theta \nu_a), \\ \nu_1 &= \cos \alpha (\cos \theta \nu_e - \sin \theta \nu_a) - \sin \alpha \nu_s, \\ \nu_2 &= \sin \theta \nu_e + \cos \theta \nu_a.\end{aligned}\tag{2}$$

The states ν_e and ν_a are characterized by the LMA oscillation parameters, θ and Δm_{12}^2 . They mix in the mass eigenstates ν_1 and ν_2 with the eigenvalues m_1 , and m_2 . The sterile neutrino is mainly present in the mass eigenstate ν_0 (mass m_0). It mixes weakly ($\sin \alpha \ll 1$) with active neutrinos in the mass eigenstate ν_1 ². We will assume first that $m_2 > m_0 > m_1$ and consider the oscillation parameters of ν_s in the intervals:

$$\Delta m_{01}^2 = m_0^2 - m_1^2 = (0.2 - 2) \times 10^{-5} \text{ eV}^2, \quad \sin^2 2\alpha \sim 10^{-5} - 3 \cdot 10^{-3}.\tag{3}$$

Let ν_{1m} , ν_{2m} , ν_{0m} be the eigenstates, and λ_1 , λ_2 , λ_0 the corresponding eigenvalues of the 3ν -system in matter. We denote the ratio of mass squared differences as

$$R_\Delta \equiv \frac{\Delta m_{01}^2}{\Delta m_{21}^2}.\tag{4}$$

²The introduction of mixing with the third active neutrino is straightforward. This mixing (if not zero) can produce small averaged oscillation effect and in what follows it will be neglected.

The level crossing scheme, that is, the dependence of λ_i , ($i = 0, 1, 2$) on the distance inside the Sun (or on the density), is shown in fig. 1. It can be constructed analytically considering mixing of the sterile neutrino (the s -mixing) as a small perturbation.

1). In the absence of s -mixing we have usual LMA system of two active neutrinos with eigenstates ν_{1m}^{LMA} , ν_{2m}^{LMA} , and the eigenvalues λ_1^{LMA} and λ_2^{LMA} which we will call the LMA levels:

$$\lambda_1^{LMA} = \frac{m_1^2 + m_2^2}{4E} + \frac{V_e + V_a}{2} - \sqrt{\left(\frac{\Delta m_{21}^2}{4E} \cos 2\theta - \frac{V_e - V_a}{2}\right)^2 + \left(\frac{\Delta m_{21}^2}{4E} \sin 2\theta\right)^2}, \quad (5)$$

and λ_2^{LMA} has similar expression with plus sign in front of square root. Here $V_e = \sqrt{2}G_F(n_e - 0.5n_n)$, and $V_a = -0.5\sqrt{2}G_F n_n$ are the matter potentials for the electron and non-electron active neutrinos respectively; n_e and n_n are the number densities of the electrons and neutrons. For the sterile neutrino we have $V_s = 0$. The 1-2 (LMA) resonance condition determines the LMA resonance energy:

$$E_a = \frac{\Delta m_{21}^2 \cos 2\theta}{2(V_e - V_a)}. \quad (6)$$

2). Let us turn on the ν_s -mixing. In the assumption $m_1 < m_0 < m_2$ the sterile neutrino level λ_s crosses λ_1^{LMA} only. The level λ_2^{LMA} essentially decouples. It is not affected by the s -mixing, and $\lambda_2 \approx \lambda_2^{LMA}$. Evolution of the corresponding eigenstate, ν_{2m} , is strongly adiabatic.

3). In general, the sterile level, λ_s , as the function of density, crosses λ_1^{LMA} twice: above and below the 1-2 resonance density. Effects of the higher (in density) level crossing can be neglected since the neutrinos of relevant energies are produced at smaller densities. This can be seen in the fig. 1 where the second crossing of λ_1^{LMA} and λ_s would be on the left, if the density would continue to increase above the central solar density. Consequently, there are two relevant resonances in the system associated with 1-2 level crossing (the LMA resonance) and with 1- s crossing. For low energies (below the s -resonance) $\lambda_1 \approx \lambda_1^{LMA}$ and $\lambda_0 \approx \lambda_s$.

The Hamiltonian of the $(\nu_{1m}^{LMA} - \nu_s)$ sub-system can be obtained diagonalizing the $\nu_e - \nu_a$ block of the 3ν Hamiltonian, and then neglecting small 1-3 element. As a result

$$H = \begin{pmatrix} \lambda_1^{LMA} & \frac{\Delta m_{01}^2}{4E} \sin 2\alpha \cos(\theta - \theta_m) \\ \frac{\Delta m_{01}^2}{4E} \sin 2\alpha \cos(\theta - \theta_m) & \frac{m_1^2 + m_0^2}{4E} + \frac{\Delta m_{01}^2}{4E} \cos 2\alpha \end{pmatrix}, \quad (7)$$

where λ_1^{LMA} is given in (5). The 1- s resonance condition,

$$\lambda_1^{LMA}(\Delta m_{21}^2/E, \theta, V_e, V_a) = \frac{m_1^2 + m_0^2}{4E} + \frac{\Delta m_{01}^2 \cos 2\alpha}{4E}, \quad (8)$$

determines the s -resonance energy

$$E_s = \frac{0.5m_1^2 + \Delta m_{01}^2 \cos^2 \alpha}{V_e + V_a} \times \frac{1 - R_\Delta}{1 - 2R_\Delta + \xi \cos 2\theta + \sqrt{(1 - 2R_\Delta + \xi \cos 2\theta)^2 - 4R_\Delta(1 - R_\Delta)(\xi^2 - 1)}}, \quad (9)$$

where $\xi \equiv (V_e - V_a)/(V_e + V_a) = n_e/(n_e - n_n)$. Notice that since λ_1^{LMA} is a non-linear function of the neutrino energy, the proportionality $E_s \propto \Delta m_{01}^2$ is broken and E_s turns out to be complicated function of Δm_{01}^2 .

Another feature of the $\nu_{1m}^{LMA} - \nu_s$ sub-system is that due to dependence of θ_m on E , the effective mixing parameter in (7), $\propto \sin 2\alpha \cos(\theta - \theta_m)$, also depends on the energy (decreases with E), though this dependence is weak. Indeed, in the case of small α and the s -resonance being substantially below the LMA resonance, we can take $\theta \approx \theta_m$ in the first approximation, $\cos(\theta - \theta_m) \approx 1$. Even in the LMA resonance, when $\theta_m = \pi/2$, we get $\cos(\theta - \theta_m) = 0.97$.

3 Survival probability. Properties of the dip

Let us find the ν_e survival probability. According to (2) the initial neutrino state can be written in terms of the matter eigenstates ν_{im} as

$$\nu_e = \sin \theta_m^0 \nu_{2m} + \cos \theta_m^0 (\cos \alpha_m^0 \nu_{1m} + \sin \alpha_m^0 \nu_{0m}), \quad (10)$$

where θ_m^0 and α_m^0 are the mixing angles in matter in the neutrino production point.

Propagation of neutrinos from the production point to the surface of the Sun is described in the following way. ν_{2m} evolves adiabatically, so that $\nu_{2m} \rightarrow \nu_2$. Evolution of the two other eigenstates is, in general, non-adiabatic, so that

$$\nu_{1m} \rightarrow A_{11}\nu_1 + A_{01}\nu_0, \quad \nu_{0m} \rightarrow A_{10}\nu_1 + A_{00}\nu_0, \quad (11)$$

where A_{ij} are the transition amplitudes which satisfy the following equalities: $|A_{01}|^2 = |A_{10}|^2 = 1 - |A_{00}|^2 = 1 - |A_{11}|^2 \equiv P_2$. They can be found by solving the evolution equation with the Hamiltonian (7). P_2 is the two neutrino jump probability in the system $\nu_{1m} - \nu_s$.

Using (10, 11) we can write the final neutrino state as

$$\nu_f = \sin \theta_m^0 \nu_2 e^{i\phi_2} + \cos \theta_m^0 [\cos \alpha_m^0 (A_{11}\nu_1 + A_{01}\nu_0) + \sin \alpha_m^0 (A_{10}\nu_1 + A_{00}\nu_0)], \quad (12)$$

where ϕ_2 is the phase acquired by ν_{2m} . Then the survival probability is given by

$$P_{ee} \equiv |\langle \nu_e | \nu_f \rangle|^2 \approx \sin^2 \theta_m^0 \sin^2 \theta + \cos^2 \theta_m^0 \cos^2 \theta [\cos^2 \alpha_m^0 - P_2 \cos 2\alpha_m^0]. \quad (13)$$

Here we have neglected a small admixture of ν_e in ν_0 : $\langle \nu_e | \nu_0 \rangle \approx 0$. Also we have taken into account that the coherence of the mass eigenstates is destroyed on the way from the Sun to the Earth due to a spread of the wave packets and averaging effects.

Similarly we obtain the transition probability of the electron to sterile neutrino:

$$P_{es} \equiv |\langle \nu_s | \nu_f \rangle|^2 \approx \cos^2 \theta_m^0 [\sin^2 \alpha_m^0 + P_2 \cos 2\alpha_m^0]. \quad (14)$$

Let us consider specific limits of the formula (13). If evolution is adiabatic in the s -resonance (which can be realized for the large enough s -mixing), we find $P_2 = 0$ and

$$P_{ee} = \sin^2 \theta_m^0 \sin^2 \theta + \cos^2 \theta_m^0 \cos^2 \theta \cos^2 \alpha_m^0. \quad (15)$$

In the opposite case of strongly non-adiabatic conversion ($P_2 \approx 1$) the probability equals

$$P_{ee} \approx \sin^2 \theta_m^0 \sin^2 \theta + \cos^2 \theta_m^0 \cos^2 \theta \sin^2 \alpha_m^0. \quad (16)$$

Notice that in spite of strong violation of adiabaticity in the s -resonance, the effect of s -mixing is still present due to the averaging of oscillations.

The energy dependences of the probabilities can be easily understood using the results given in Eqs. (13 - 16). Let $E_a(n_c)$ and $E_s(n_c)$ be the LMA resonance energy and the s -resonance energy which correspond to the central density of the Sun n_c . Then the following consideration holds.

1). For high energies, $E > E_a(n_c)$, neutrinos are produced far above the 1-2 resonance density, so that $\theta_m^0 \approx \pi/2$. Then according to (13), $P = \sin^2 \theta$, as in the 2ν case, independently of properties of the s -resonance. The initial state coincides practically with ν_{2m} , and the later propagates adiabatically.

The s -resonance becomes operative at the energies of adiabatic edge, when θ_m^0 deviates from $\pi/2$. This is the consequence of the fact that λ_s crosses the lowest LMA level λ_1 .

2). For low energies, $E < E_s(n_c)$, the s -resonance is not realized inside the Sun and s -mixing equals the vacuum mixing ($\cos^2 \alpha_m^0 \approx \cos^2 \alpha^0 \approx 1$). Then from (13) we get the usual adiabatic formula for the 2ν case

$$P_{ee}^{adiab} \approx \sin^2 \theta_m^0 \sin^2 \theta + \cos^2 \theta_m^0 \cos^2 \theta. \quad (17)$$

3). At the intermediate energies, crossing the s -resonance can be adiabatic (at $E \sim E_s(n_c)$), and moreover, the initial angle can be equal to $\alpha_m^0 \approx \pi/2$. Since the s -resonance is very narrow this equality is realized already at energies slightly above $E_s(n_c)$. In this case we get from (15)

$$P_{ee} \approx \sin^2 \theta_m^0 \sin^2 \theta. \quad (18)$$

If also $E \ll E_a(n_c)$, so that $\theta_m^0 \approx \theta$, the Eq. (18) leads to

$$P_{min} = P_{ee} \approx \sin^4 \theta. \quad (19)$$

P_{min} is the absolute minimum of the survival probability which can be achieved in the system. In general, $P_{ee} > \sin^4 \theta$, since E is not small in comparison with E_a ($\sin \theta_m^0 > \sin \theta$) and/or the adiabaticity is broken.

For $\alpha_m^0 \approx \pi/2$, which can be realized for E being slightly higher than E_s , we find from (13)

$$P_{ee} \approx \sin^2 \theta_m^0 \sin^2 \theta + \cos^2 \theta_m^0 \cos^2 \theta \sin^2 \alpha_m^0 P_2. \quad (20)$$

With the increase of energy the adiabaticity is violated, $P_2 \rightarrow 1$, and the probability approaches the adiabatic one for the 2ν system (17).

In fig. 2 we show results of numerical computations of the ν_e survival probability P_{ee} , and the survival probability of active neutrinos, $(1 - P_{es})$, as functions of energy. In our numerical calculations we have performed a complete integration of the evolution equations for the 3ν -system and also made averaging over the production region of the Sun. The analytical consideration allows us to understand immediately the numerical results shown in fig. 2.

The effect of s -mixing is reduced to appearance of a dip in the LMA energy profile. A size of the dip equals:

$$\Delta P_{ee} \equiv P_{ee}^{LMA} - P_{ee} = P_{es} \cos^2 \theta, \quad (21)$$

where $P_{ee}(E)^{LMA} = P_{ee}(E)^{adiab}$ is the LMA probability given by the adiabatic formula (13). To obtain the last equality in (21) we used expressions for P_{ee} from (13), $P_{ee}(E)^{LMA}$ - from (17) and P_{es} - from (14). Since $\cos^2 \theta < 1$ (the best fit value of LMA mixing, $\cos^2 \theta = 0.714$) according to (21) a change of the ν_e survival probability due to mixing with ν_s is weaker than the transition to sterile neutrino P_{es} . The relation (21) is well reproduced in fig. 2.

A position of the dip (its low energy edge) is given by the resonance energy taken at the central density of the Sun $E_s(n_c)$ (9). With increase of Δm_{01}^2 the dip shifts to higher energies. However, this shift is stronger than simple proportionality to Δm_{01}^2 as can be found from (9). For instance, the increase of R_Δ from 0.1 to 0.2 leads to the shift of dip by factor 2.6 in the energy scale (see fig. 2).

The maximal suppression in the dip depends on R_Δ and α . For small R_Δ (large split between the two resonances) and large α ($\sin^2 2\alpha > 10^{-3}$) the absolute minimum (19) can be achieved. Indeed, the condition for the minimum is nearly satisfied for the solid line in the upper panel of fig. 2 where $P_{ee} \sim 0.1$.

With increase of R_Δ (smaller split of the resonances) or/and decrease of α (stronger violation of the adiabaticity) a suppression in the dip weakens. Also with decrease of α the dip becomes narrower.

Similarly one can consider crossing of λ_s with λ_2^{LMA} . In this case the effect on P_{ee} is weaker due to smaller admixture of ν_e in ν_2 . Now the dip can appear at higher energies in the non-oscillatory part of the LMA profile where $P_{ee} \approx \sin^2 \theta$.

4 Observables and restrictions

As follows from fig. 2, selecting appropriately the values of R_Δ and α (and therefore position and form of the dip) one can easily obtain significant suppression of Q_{Ar} as well as the upturn of the spectrum (see fig. 3). There are, however, restrictions which follow from other experimental results.

1). *Ar-production rate versus Ge-production rate.* A decrease of Q_{Ar} is accompanied by decrease of Q_{Ge} (fig. 3). Since the LMA prediction for Q_{Ge} is close to the central experimental value a possible decrease of Q_{Ge} is restricted. Let us consider this correlation in details.

The decrease of the *Ar*-production rate can be written as

$$\Delta Q_{Ar} = Q_{Ar}^{Be} \cdot \Delta P_{ee}^{Be} + Q_{Ar}^{int} \cdot \Delta P_{ee}^{int} + Q_{Ar}^B \cdot \Delta P_{ee}^B, \quad (22)$$

where $Q_{Ar}^{Be} = 1.15$ SNU, $Q_{Ar}^{int} = 0.64$ SNU and $Q_{Ar}^B = 5.76$ SNU are the contributions to the *Ar*-production rate from the *Be*-flux, the fluxes of the intermediate energies (*pep*, *CNO*) and the *B*-neutrino flux according to SSM [9]. Here ΔP_{ee}^{Be} is the change of survival probability at E_{Be} , ΔP_{ee}^{int} and ΔP_{ee}^B are the changes of the effective (averaged over appropriate energy interval) survival probabilities for the intermediate energy fluxes and the boron neutrino flux respectively.

The suppression of the *Ge*- production rate equals

$$\Delta Q_{Ge} \approx Q_{Ge}^{Be} \cdot \Delta P_{ee}^{Be} + Q_{Ge}^{int} \cdot \Delta P_{ee}^{int} + Q_{Ge}^B \cdot \Delta P_{ee}^B, \quad (23)$$

where $Q_{Ge}^{Be} = 34.2$ SNU, $Q_{Ge}^{int} = 11.7$ SNU and $Q_{Ge}^B = 12.1$ SNU are the contributions to the *Ge*-production rate for the *Be*-neutrino flux, the sum of *pep*- and *CNO*- fluxes, and the *B*-neutrino flux correspondingly. ΔP_{ee}^{Be} is the same as in (22), whereas ΔP_{ee}^{int} and ΔP_{ee}^B are approximately equal to those in (22).

The changes of rates are correlated:

$$\Delta Q_{Ge} = A(R_\Delta, \alpha) \cdot \Delta Q_{Ar}, \quad (24)$$

where A is the constant which depends on the oscillation parameters. If the *Be*- (ν_e) line is suppressed only, we would have $A^{Be} \approx 30$. If the neutrino fluxes at the intermediate energies are affected only, then $A^{int} \sim 18$, for the boron neutrino flux we find the smallest value $A^B \sim 2$.

In principle, the decrease of the *Ge*-production rate can be compensated by increase of the survival probability for the *pp*-neutrinos. This probability is given approximately by the average vacuum oscillations formula

$$P_{ee}(pp) \approx 1 - 0.5 \sin^2 2\theta. \quad (25)$$

From Eq. (25) it follows that the increase of $P_{ee}(pp)$ requires the decrease of mixing:

$$\Delta \sin^2 \theta = -\frac{\Delta P_{ee}(pp)}{2\sqrt{2P_{ee}(pp) - 1}}. \quad (26)$$

The SSM contribution of the pp -neutrinos to Q_{Ge} equals $Q_{Ge}^{pp} = 69.7$ SNU, therefore to compensate 1σ (~ 5 SNU) decrease of Q_{Ge} , one needs $\Delta P_{ee}(pp) = 0.07$. For this value of $\Delta P_{ee}(pp)$ eq. (26) gives $\Delta \sin^2 \theta = -0.1$. However, a decrease of $\sin^2 \theta$ is restricted by the high energy data (SK, SNO). Indeed, the survival probability for the boron neutrinos with $E > 5$ MeV is proportional to $\sin^2 \theta$:

$$P_B \approx a \sin^2 \theta, \quad a \approx 1.1, \quad (27)$$

where the deviation of a from 1 is due to effects of the upturn and the ν_e regeneration in the matter of the Earth. So, the survival probabilities for the pp - and B -neutrinos are related:

$$P_{pp} \approx 1 - \frac{2}{a}P_B + \frac{2}{a^2}P_B^2. \quad (28)$$

For the best fit value of mixing ($\sin^2 \theta \sim 0.285$) this equality gives $\Delta P_{pp} \approx -0.78\Delta P_B$. In turn, the survival probability $P_B(> 5 \text{ MeV})$ is fixed by the CC/NC ratio:

$$\frac{CC}{NC} = \frac{P_B}{1 - \eta_s(1 - P_B)}, \quad (29)$$

where η_s is the sterile neutrino fraction in the state to which ν_e transforms. This relation does not depend on the original Boron neutrino flux. The solar neutrino data restrict $\eta_s < 0.2$, and therefore the presence of sterile component allows us to reduce the probability by a small amount only: $\Delta P_{ee} \sim (0.2 - 0.3)\eta_s < 0.06$. Moreover, according to fig. 2, the contribution of sterile neutrino to the high energy part of the spectrum is even smaller than 0.2.

2). *The Ar-production rate versus the rates at SNO and SuperKamiokande.* For large R_Δ and $\sin \alpha$ the restriction appears from the charged current (CC) - event rate at SNO and well as from the rate of events at SK and the spectra. For free boron neutrino flux the suppression of Q_{Ar} due to suppression of the boron electron neutrino flux can be written as

$$\Delta Q_{Ar} = Q_{Ar}^B f_B \Delta P_{ee}^{B,Ar}, \quad (30)$$

where $f_B \equiv F_B/F_B^{SSM}$ is the total boron neutrino flux in the units of the SSM flux. For the relative change of flux measured in CC-event, $\Delta[CC] \equiv \Delta F_{CC}/F_{CC}^{SSM}$ we have

$$\Delta[CC] = f_B \Delta \tilde{P}_{ee}^B, \quad (31)$$

where $\Delta \tilde{P}_{ee}^B$ is the change of the effective survival probability for the SNO energy range. With decrease of Q_{Ar} the rate $[CC]$ decreases; we find

$$\Delta[CC] = 0.2Q_{Ar}, \quad (32)$$

and this relation does not depend of f_B , so that for a given Q_{Ar} , the decrease of $[CC]$ can not be compensated by increase of f_B .

Also the spectral information does not allow to strongly suppress Q_{Ar} .

5 Global Fit

We have performed the global fit of the solar neutrinos data which takes into account the correlations of observables discussed in sec. 4. We use the same procedure of the fit as in our previous publications [7, 10]. In fig. 4 we show the dependence of the χ^2 on R_Δ for fixed value of Δm_{21}^2 .

The following comments are in order.

1. According to the fig. 4 the minimum $\chi_0^2 \sim 65.2$ is achieved for

$$R_\Delta = 0.9 \quad \sin^2 2\alpha = 10^{-3}. \quad (33)$$

It corresponds to the unmodified Be - flux but suppressed pep - and CNO - fluxes. The upturn of the energy spectrum above 5 MeV is practically eliminated. χ_0^2 can be compared with $\chi^2 \sim 66.6$, for zero s -mixing. The improvements of the fit, $\Delta\chi^2 = 1.4$, is not substantial. Notice however, that value χ_0^2 is not the absolute minimum. Furthermore, one should not expect significant improvement of the fit since the original pull was about 2σ only, and quality of the global fit is very good in both cases. Finally with sterile neutrinos we have modified solution of solar neutrino problem with different set of predictions for observables.

2. As follows from the fig. 4 certain regions of parameters of the sterile neutrino are strongly disfavored or excluded already by existing data. In particular, the region $\sin^2 2\alpha = 3 \cdot 10^{-4}$ and $R_\Delta < 0.07$ is excluded. It corresponds to strong suppression of the Be electron neutrino flux.

In another strongly disfavored region: $R_\Delta = 0.10 - 0.25$, $\sin^2 2\alpha > 10^{-3}$, one has substantial suppression of the CC -signal at SNO and SK as well as distortion of the boron electron neutrino spectrum. For larger values of sterile neutrino mass, $R_\Delta > 0.25$, the dip shifts to higher energies and disappears. The conversion effects (and corresponding χ^2) converge to the pure LMA solution case .

6 Three scenarios

Three phenomenologically different scenarios can be realized depending on the oscillation parameters, and therefore on the position and form of the dip. Three panels in the fig. 3, which correspond to different values of R_Δ , illustrate these scenarios. Let us describe features of these three possibilities.

1). Narrow dip at low energies: the Be -line is in the dip. This corresponds to $\sin^2 2\alpha < 10^{-4}$ and $R_\Delta < 0.08$ or

$$0.5E_{Be} < E_s(n_c) < E_{Be}, \quad (34)$$

where $E_{Be} = 0.86$ MeV is the energy of the Be -neutrinos (first panel in fig. 2 and solid line in fig. 3). The lower bound (34) implies that the pp -neutrino flux is not affected. In this case the Be -line is suppressed most strongly; the ν_e fluxes of the intermediate energies (pep and CNO neutrinos) are suppressed weaker and the low energy part of the boron neutrino spectrum measured by SK and SNO is practically unaffected (see fig. 3).

According to fig. 3 the value of coefficient in Eq. (24) $A = 24$. Taking the present 1σ errors, 0.23 SNU and 5 SNU, for the Homestake and the combined Gallium result correspondingly, we find that the central experimental value of Q_{Ar} can be reached at the price of the 2σ decrease of Q_{Ge} .

The best compromise solution would correspond to $\sin^2 2\alpha \sim 7 \cdot 10^{-5}$, when Q_{Ar} is 1σ above the observation, and Q_{Ge} is 1σ below the observation. In this case the BOREXINO rate reduces from 0.61 down to 0.48 of the SSM rate (see sect. 7).

For $E_s(n_c)$ being substantially smaller than E_{Be} , the Be -line is on the non-adiabatic edge of the dip and its suppression is weaker. In this case larger values of $\sin \alpha$ are allowed.

As we have discussed in sec.4 variations of the LMA parameters and the original boron neutrino flux do not allow us to compensate completely the changes of the observables (which worsen the fit) in the case when the Be -line is suppressed.

2). The dip at the intermediate energies:

$$E_{Be} < E_s(n_c) < 1.4 \text{ MeV} \quad (35)$$

(see the second panel in fig. 2 and the dashed lines in fig. 3). The Be -line is out of the dip and therefore unaffected. A decrease of Q_{Ar} occurs due to suppression of the ν_e components of the pep - and CNO - neutrino fluxes.

In this case a decrease of Q_{Ar} is accompanying by smaller decrease of Q_{Ge} in comparison with the previous case. For small enough mixing (so that the boron neutrinos are not affected strongly) we get from fig. 3 $A = 15$ in the relation (24). For larger $\sin^2 2\alpha$ a suppression of the boron ν_e flux becomes substantial and A decreases further: $A \sim 12$. Now the value $Q_{Ar} = 2.8$ SNU, which is 1σ above the observation, can be achieved by just 0.4σ reduction of Q_{Ge} .

The BOREXINO signal due to the Be -flux is unchanged, and also the observable part of the boron neutrino flux is affected very weakly. Change of the CC/NC ratio is about 0.002.

The optimal fit (see fig. 4) would correspond to $\sin^2 \alpha = 10^{-3}$, when Q_{Ar} is diminished down to 2.75 SNU, at the same time $Q_{Ge} = 68$ SNU and CC/NC = 3.22 in agreement with the latest data [2].

3). The dip at high energies:

$$E_s(n_c) > 1.6 \text{ MeV} \quad (36)$$

(see fig. 2, the panel for $R_\Delta = 0.2$, and the dotted lines in fig. 3). Q_{Ar} is diminished due to suppression of the low energy part of the boron neutrino spectrum. For $\sin^2 \alpha = 10^{-3}$, we find $\Delta Q_{Ar} = 0.17 \text{ SNU}$. At the same time a decrease of the Ge -production rate is very small: $\Delta Q_{Ge} \sim 0.5 \text{ SNU}$ which corresponds to $A = (2 - 3)$ in eq. (24).

At $\sin^2 \alpha = 10^{-3}$ there is already significant modification of the observable part of the boron neutrino spectrum and decrease of the total rate at SK and SNO. Also the CC/NC ratio decreases. According to fig. 3 at $\sin^2 2\alpha = 10^{-3}$, we have $\Delta(\text{CC/NC}) = 0.01$. Further increase of R_Δ will shift the dip to higher energies, where the boron neutrino flux is larger. This, however, will not lead to further decrease of Q_{Ar} since the dip becomes smaller approaching the non-oscillatory region (see fig. 2). The BOREXINO signal (Be -line) is unchanged. So, the main signature of this scenario is a strong suppression of the upturn and even a possibility to bend the spectrum down.

Even for large R_Δ the influence of ν_s on the KamLAND results is negligible due to very small mixing. In contrast to the solar neutrinos, for the KamLAND experiment the matter effect on neutrino oscillations is very small and no enhancement of the s -mixing occurs. Therefore the effect of s -mixing on oscillation probability is smaller than $\sin^2 2\alpha \sim 10^{-3}$. For this reason the KamLAND result has not been included in the fit of data.

7 Further tests

How one can check the described scenarios?

1) BOREXINO and KamLAND (solar) as well future low energy experiments [19, 20, 21, 22, 23, 24, 25] can establish the suppression of the Be -neutrino flux in comparison with the LMA predictions, if the case 1) is realized. In BOREXINO and other experiments based on the νe -scattering the ratio of the numbers of events with and without conversion can be written as

$$R_{Borexino} = P_{ee}(1 - r) + r - rP_{es}, \quad (37)$$

where $r \equiv \sigma(\nu_\mu e)/\sigma(\nu_e e)$ is the ratio of cross-sections. Using Eq. (21) we find an additional suppression of the BOREXINO rate in comparison with the pure LMA case:

$$\Delta R_{Borexino} \equiv R_{Borexino}^{LMA} - R_{Borexino} = (1 - r)\Delta P_{ee} + rP_{es} \approx \Delta P_{ee}(1 + r \tan^2 \theta). \quad (38)$$

According to fig. 3, $R_{Borexino}^{LMA}$ can be diminished rather significantly. However, if the prediction for Q_{Ge} is 2σ (or less) below the experimental results, we find $R_{Borexino}^{LMA} > 0.4$ and $\Delta R_{Borexino} < 0.2$. For the best fit value in the scenario 1):

$$R_{Borexino}^{LMA} \sim 0.5, \quad (\Delta R_{Borexino} \sim 0.1). \quad (39)$$

Clearly, it will be difficult to establish such a difference. Furthermore, an additional suppression is mainly due to conversion to the sterile neutrino and the problem is to distinguish the conversion effect and lower original flux: the CC/NC ratio can not be used. Therefore not only high statistics results but also precise knowledge of the original fluxes is needed. The *pep*-flux is well known, however predictions of the *CNO* neutrino fluxes have larger uncertainties.

2). It may happen that the dip is at higher energies and the *Be*- flux is unaffected. In this case one expects significant suppression of the *pep*- and *CNO*- fluxes. Such a possibility can be checked using combination of measurements from different experiments which are sensitive to different parts of the solar neutrino spectrum. The radiochemical *Li*- experiment [26] has high sensitivity to the *pep*- and *CNO*- neutrino fluxes [27]. According to SSM [9], the *CNO*-neutrino contribution to the *Be*-production rate in this experiment is $Q_{Be}^{CNO} = 14.2$ SNU of the total rate $Q_{Be}^{CNO} = 52.3$ SNU, so that $Q_{Be}^{CNO}/Q_{Be} = 0.27$. For the *Cl*- and *Ga*- experiments the corresponding ratios are substantially smaller: $Q_{Ar}^{CNO}/Q_{Ar} = 0.05$ and $Q_{Ge}^{CNO}/Q_{Ge} = 0.07$. For the *pep*-neutrinos we get $Q_{Be}^{pep}/Q_{Be} = 0.176$.

Precise measurements of Q_{Be} and Q_{Ge} and independent measurements of the *B*, *pp* and *Be* neutrino fluxes and subtraction of their contributions from Q_{Be} and Q_{Ge} will allow to determine the *CNO*- electron neutrino fluxes. In general, to measure oscillation parameters and to determine the original solar neutrino fluxes one will need to perform a combined analysis of results from *Ga*-, *Cl*-, *Li*- experiments as well as the dedicated low energy experiments [19, 20, 21, 22, 23, 24, 25]. Of course, new high statistics *Cl*-experiment would clarify the situation directly.

3). For $R_{\Delta} \sim 0.1 - 0.2$ and $\sin^2 2\alpha \sim 10^{-3}$ one expects significant suppression of the low energy part of the *B*- neutrino spectrum. As follows from figs. 5, at 5 MeV an additional suppression due to sterile neutrino can reach (10 - 15)% both in SK and SNO. The spectra with the *s*-mixing give slightly better fit to the data. Notice that there is no turn down of the SNO spectrum for $R_{\Delta} = 0.2$ and $\sin^2 \theta_{13} = 10^{-3}$ due to an additional contribution from the $\nu - e$ scattering. Precision measurements of shape of the spectrum in the low energy part ($E < 6 - 8$ MeV) will give crucial checks of the described possibility.

4). In supernovae, neutrinos are produced at densities far above the LMA resonance density and propagation is adiabatic in the LMA resonance. So, even for very small 1-3 mixing ($\sin^2 \theta_{13} > 10^{-4}$) the adiabatic conversion $\nu_e \rightarrow \nu_2$ is realized without any effect of sterile neutrino (as in the case described in Eq. (17)). If, however, the sterile level crosses the second level λ_2^{LMA} one may expect some manifestations of the sterile neutrino in the ν_e channel, provided that the mass hierarchy is inverted or the 1-3 mixing is very small ($\sin^2 \theta_{13} < 10^{-4}$).

5). Smallness of mixing of the sterile neutrino allows one to satisfy the nucleosynthesis bound: such a neutrino does not equilibrate in the Early Universe. For this reason sterile neutrinos also do not influence the large scale structures formation in the Universe.

6). A very small s -mixing means that the width of s -resonance is also very small. In the density scale $\Delta n/n = \tan 2\alpha \sim 10^{-2}$. Therefore 1% density perturbations can strongly affect conversion in the s -resonance [28]. If density perturbations (or density profile) change in time, this will induce time variations of neutrino signals. Since the effect of s -resonance is small, one may expect 10% (at most) variations of the Ga - and Ar - production rates.

It seems that further precision measurements of the solar neutrino signals are the only possibility to check the suggested scenarios.

8 Conclusions

1. The low (with respect to the LMA prediction) value of the Ar -production rate measured in the Homestake experiment and/or suppressed upturn of the spectrum at low energies in SK and SNO can be explained by introduction of the sterile neutrino which mixes very weakly with the active neutrinos.

2. The mixing of sterile neutrino leads to appearance of the dip in the survival probability in the interval of intermediate energies $E = 0.5 - 5$ MeV. The survival probability in the non-oscillatory and vacuum ranges is not modified (if sterile level crosses λ_1^{LMA}).

3. Depending on value of R_Δ , that is, on a position of the dip, three phenomenologically different scenarios are possible:

- (i) the Be -neutrino line in the dip;
- (ii) strong suppression of the pep - and CNO - neutrino fluxes, and the Be -neutrino line out of the dip;
- (iii) suppression of the boron flux only.

The best global fit of the solar neutrino data corresponds to the unsuppressed Be -line, but strongly suppressed pep - and CNO - neutrino fluxes. Such a scenario requires $\sin^2 2\alpha \sim 10^{-3}$ and $R_\Delta \sim 0.1$. It predicts also an observable suppression of the upturn of the spectrum at SK and SNO.

4. The present experimental results as well as relations between observables restrict substantially possible effects of the dip induced by the s -mixing.

5. The presence of s -mixing can be established by future precise measurements of the Be -, pep -, CNO - neutrino fluxes in BOREXINO [18] and KamLAND, as well as by measurements of the low energy part of the Boron neutrino spectrum ($< 5 - 6$ MeV) in SNO. Study of the solar neutrinos seems to be the only possible way to test the scenarios described in this paper. There is no observable effects in laboratory experiment, as well as in astrophysics and cosmology.

6. We have performed a general study of the effect of mixing with additional neutrino states

(see the Appendix). Only in the case when the sterile neutrino level crosses both the LMA levels, the effect of additional mixing can enhance the survival probability. This case is not realized, however, for additional sterile neutrino. In all other cases an additional mixing leads to suppression of survival probability.

7. Even precise measurements of the high energy part of the solar neutrino spectrum may not be enough to reconstruct the energy profile of the effect at low energies. So, the low energy solar experiments are needed and they may lead to important discoveries.

9 Note added

Since the time we posted our paper on hep-ph, some new publications have appeared which are relevant for this study.

1). Lower value of the cross-section $^{14}N(p, \gamma)^{15}O$ measured by the LUNA experiment [29] leads to decrease of the predictions for the Ar -production rate are by $\Delta Q_{Ar} = -0.1$ SNU [30] (see our footnote 1). This reduces a difference of the LMA prediction and the Homestake result by about 0.5σ . Notice that at the same time the Ge -production rate is diminished by $\Delta Q_{Ge} = 2$ SNU.

2). Larger values of the $^7Be(p, \gamma)^8B$ cross-section obtained in the recent measurements lead to significant increase of the predicted boron neutrino flux. Now the predicted flux is larger than than extracted from the NC event rate measured at SNO: $f_B = 0.88 \pm 0.04(exp) \pm 0.23(theor)$ [31]. Being confirmed this may testify for partial conversion of the produced ν_e to sterile neutrino thus supporting scenario suggested in this paper.

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Appendix: Profile of the effect and new neutrino states

As we have established in the previous sections, mixing with sterile neutrino can modify the LMA energy profile, namely, suppress the survival probability in certain energy range. Here we present a general consideration of possible modifications of the LMA energy profile by mixing with new neutrino states.

In general, an introduction of new states leads to decrease of P_{ee} , since new channels open for disappearance of ν_e . What are conditions for increase of P_{ee} ?

In the LMA case the survival probability at low energies and at high energies are uniquely

related (28). So, in principle, measurements at high energies ($E > 5$ MeV) allow to reconstruct the profile at low energies provided that Δm^2 is well determined. The latter can be achieved by KamLAND. Mixing with new states can change this high - low energy relation.

In assumption that the coherence of all mass eigenstates is lost on the way to the Earth we can write the ν_e -survival probability after propagation in the Sun as

$$P_{ee} = \sum_i a_i |U_{ei}|^2, \quad (40)$$

where $a_i \equiv |\langle \nu_i | \nu_f \rangle|^2$ is the probability to find the mass state i in the final state and $U_{ei} \equiv \langle \nu_e | \nu_i \rangle$ is the mixing parameter. The quantities in eq. (40) satisfy the normalization conditions:

$$\sum_i a_i = 1, \quad \sum_i |U_{ei}|^2 = 1. \quad (41)$$

At low energies, where neutrino conversion is due to the vacuum oscillations, the admixtures of mass eigenstates are not changed and flavors are determined. Contributions from two different mass eigenstates add incoherently. In the 2ν - case we have $a_1 = \cos^2 \theta$, $a_2 = \sin^2 \theta$, $U_{e1} = \cos \theta$, $U_{e2} = \sin \theta$, and consequently, $P_{ee} = \cos^4 \theta + \sin^4 \theta$.

The only way to increase P_{ee} in vacuum, would be to restore the coherence (at least partially) of the two contributions, or decrease the mixing. In general, one should concentrate the electron flavor on one of the mass eigenstates and increase its admixture.

Suppose additional neutrino states also produce the vacuum oscillation effect (no level crossing). Mixing of these new states with ν_e leads to decrease of $|U_{e1}|^2$ or/and $|U_{e2}|^2$, as well as a_1 and a_2 , and one can easily show that

$$P_{ee}(2) \geq P_{ee}(2 + n). \quad (42)$$

So, new states can lead to decrease of P_{ee} only.

Matter effects change a_i . At high energies for the 2ν case we get $a_1 \approx 0$ and $a_2 \approx 1$. Let $|U_{ei}|_{min}$ and $|U_{ei}|_{max}$ be the largest and smallest mixing parameters correspondingly. Then it is easy to prove inequality

$$|U_{ei}|_{min}^2 \leq P_{ee} \leq |U_{ei}|_{max}^2. \quad (43)$$

So, the only way to increase P_{ee} is to change the admixtures of the mass states in such a way that a_i , which corresponds to the largest $|U_{ei}|$, increases.

Let us consider one additional neutrino level (state) which mixes weakly with the LMA levels. Due to small mixing the LMA levels do not change significantly. If new (predominantly sterile) level crosses one of the LMA level only and $P(i)$ is the probability that neutrino state does not transit to new level in this crossing, then

$$P_{ee} \approx P(1)a_1|U_{e1}|^2 + a_2|U_{e2}|^2. \quad (44)$$

Here we put $|U_{e0}| \approx 0$. Since $P(1) < 1$, the probability decreases as we have found in the specific case discussed in this paper. Similarly, if the new level crosses the second LMA level, the survival probability

$$P_{ee} \approx a_1|U_{e1}|^2 + P(2)a_2|U_{e2}|^2 , \quad (45)$$

decreases. Notice that if neutrino is produced far above the LMA resonance, so that $a_1 \approx 0$, the probability equals $P_{ee} \approx P(2)a_2|U_{e2}|^2$ and for small $P(2)$ (adiabaticity) the probability P_{ee} can be strongly suppressed.

To enhance P_{ee} the new level should cross both LMA levels (in this case formulas above are not valid). If both crossings are adiabatic, the following transitions occur:

$$\nu_e \approx \nu_{2m} \rightarrow \nu_{0m} \rightarrow \nu_{1m} . \quad (46)$$

So that $P_{ee} = \cos^2 \theta$. If transitions are partially adiabatic, we find $\sin^2 \theta < P_{ee} < \cos^2 \theta$. Thus, the admixture of the mass state with the largest fraction of the electron neutrinos is enhanced. However, to get such a double crossing, the new level should have stronger dependence on the density than the dependence of the electron neutrino level. That is, the corresponding matter potential should be large: $V_x > V_e$. This is excluded: an additional sterile neutrino level can cross only one LMA level, thus leading to suppression of the survival probability. The results obtained in this paper are robust.

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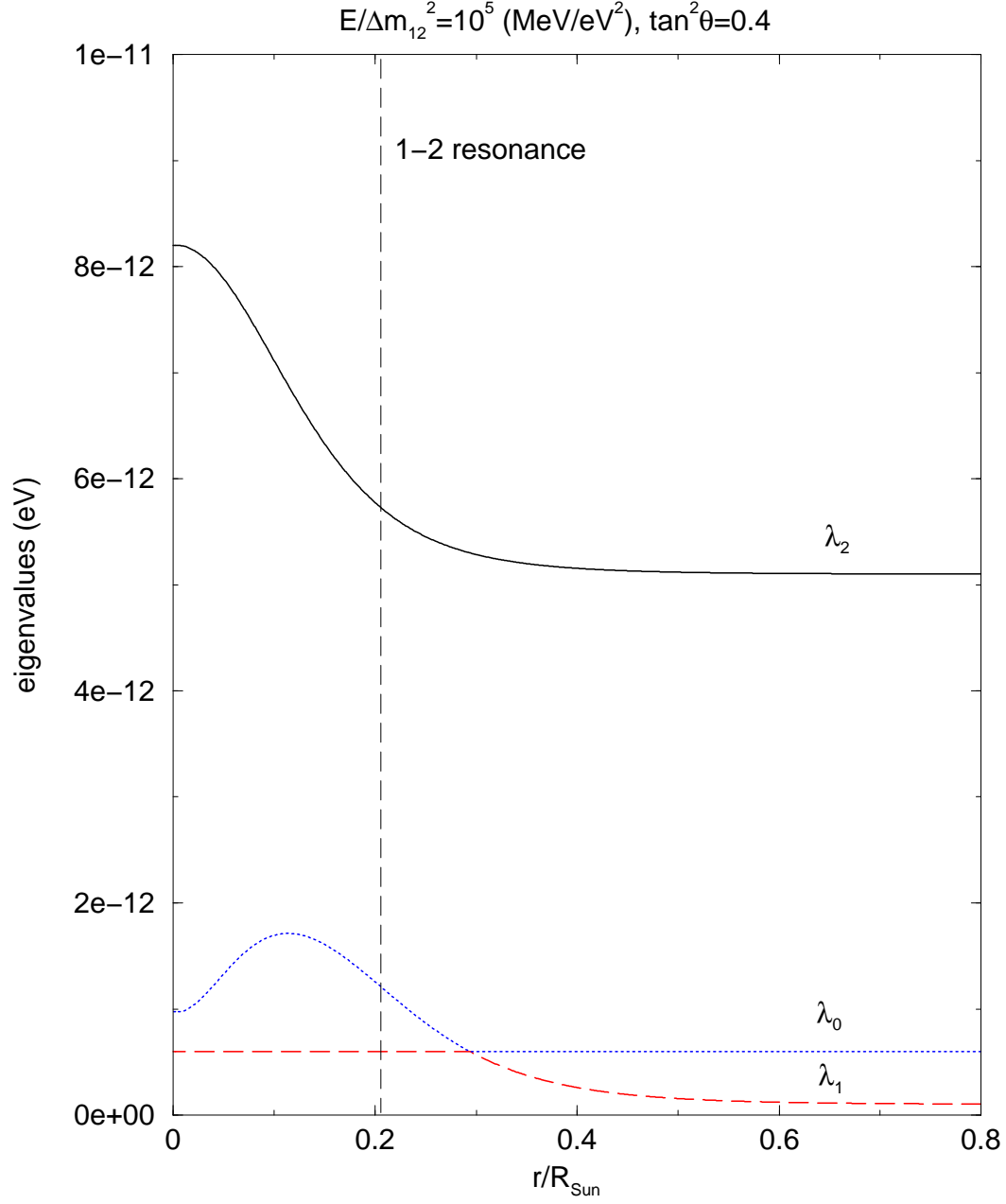


Figure 1: The level crossing scheme. The mass eigenvalues as functions of the distance from the center of the Sun for $E/\Delta m_{12}^2 = 10^5 \text{ eV}^2$ and $\tan^2 \theta = 0.4$. The mass ratio is taken to be $R_\Delta = \Delta m_{01}^2/\Delta m_{12}^2 = 0.10$. Also shown is the position of 1-2 resonance (dashed vertical line).

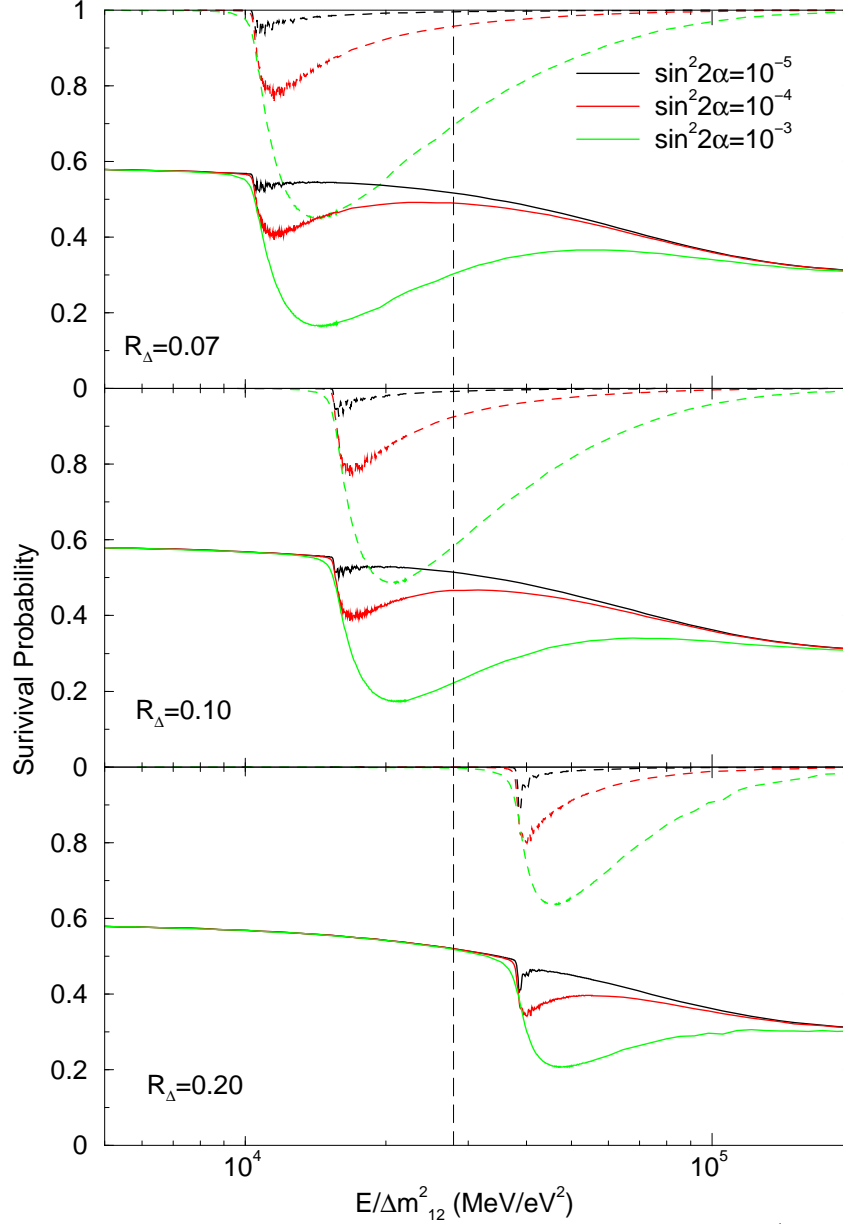


Figure 2: The survival probability of the electron neutrinos, P_{ee} , (solid line) and survival probability of the active neutrinos, $1 - P_{es}$, (dashed line), as functions of $E/\Delta m_{12}^2$ for different values of the sterile-active mixing parameter $\sin^2 2\alpha$. We take $\tan^2 \theta = 0.4$. Also shown is position of the 1-2 resonance for the central density of the Sun. (vertical dashed line). For $\Delta m_{12}^2 = 7.1 \cdot 10^{-5} \text{ eV}^2$ the Be -line is at $E/\Delta m_{12}^2 = 1.2 \cdot 10^4 \text{ MeV/eV}^2$, the pep -neutrino line is at $E/\Delta m_{12}^2 = 2 \cdot 10^4 \text{ MeV/eV}^2$, the lowest (observable) energy, $E = 5 \text{ MeV}$, and the highest energy of boron neutrino spectrum ($\sim 14 \text{ MeV}$) are at $E/\Delta m_{12}^2 = 7 \cdot 10^4 \text{ MeV/eV}^2$ and $2 \cdot 10^5 \text{ MeV/eV}^2$ correspondingly.

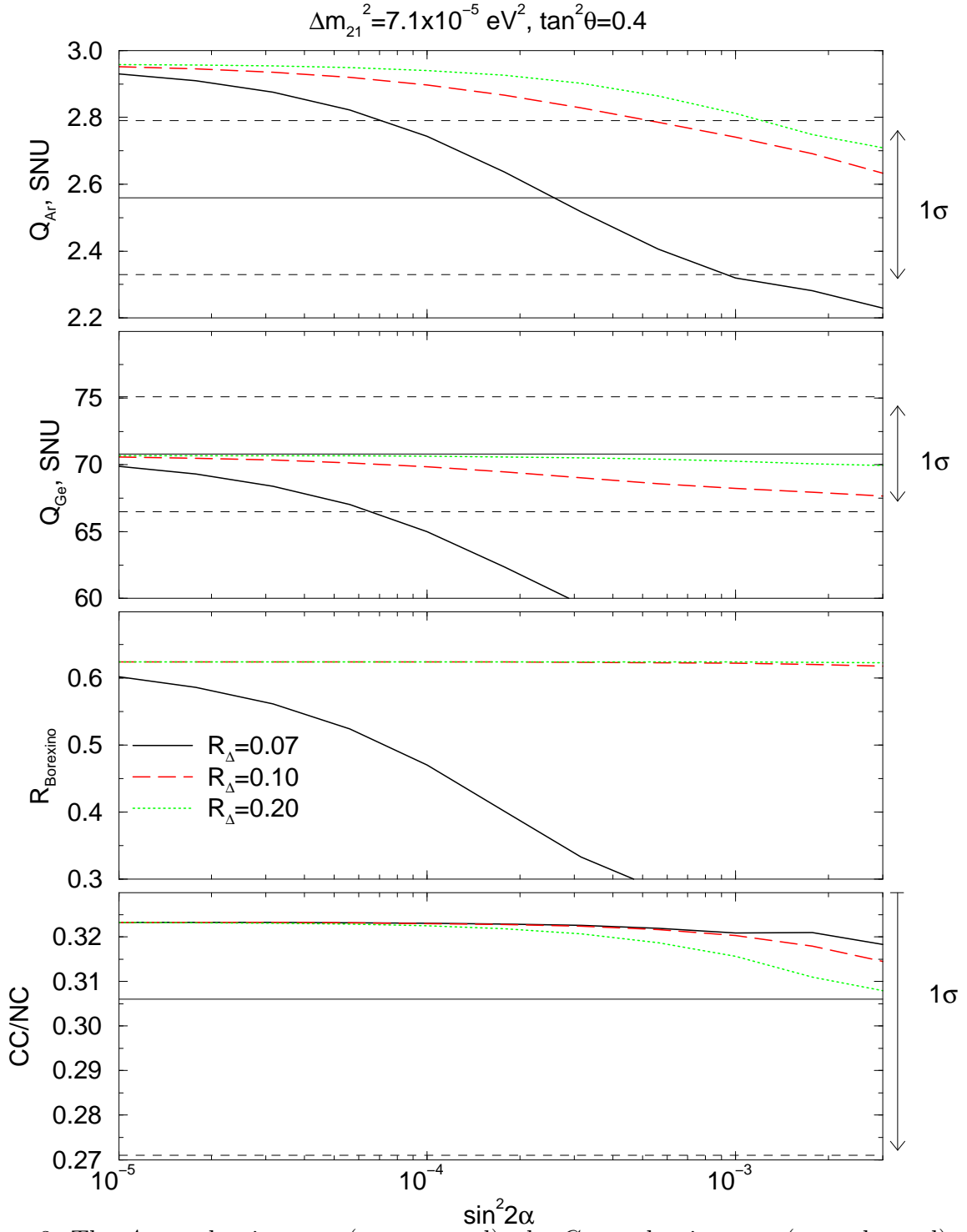


Figure 3: The Ar production rate (upper panel), the Ge production rate (second panel) the suppression factor for the BOREXINO signal and the CC/NC ratio at SNO as functions of $\sin^2 2\alpha$, for $\tan^2 \theta = 0.4$ and $\Delta m_{21}^2 = 7.1 \times 10^{-5} \text{ eV}^2$.

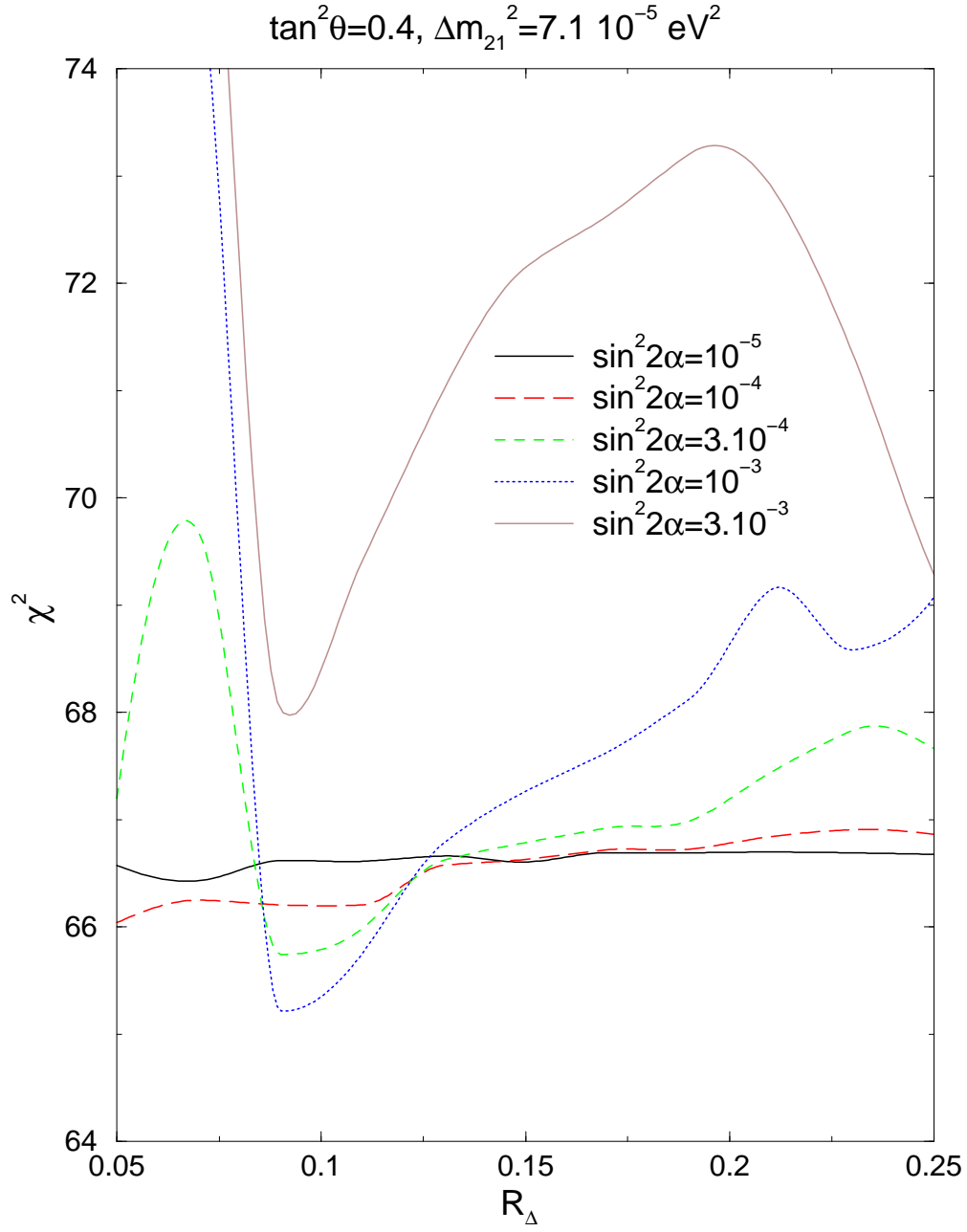


Figure 4: The χ^2 of the global fit of the solar neutrino data as a function of R_Δ for different values of the sterile-active mixing parameter $\sin^2 2\alpha$. We take $\tan^2 \theta = 0.4$ and $\Delta m_{12}^2 = 7.1 \times 10^{-5} \text{ eV}^2$,

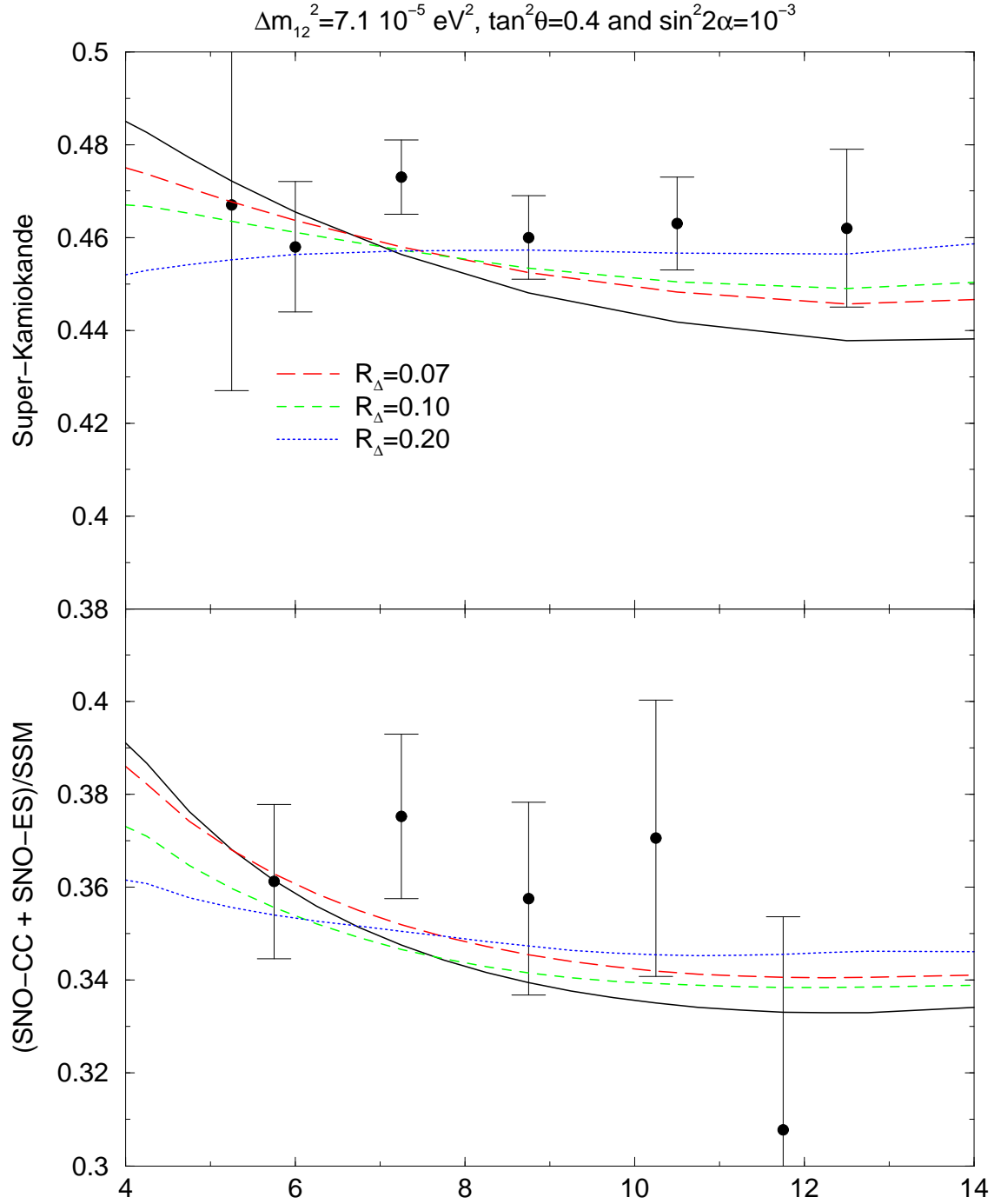


Figure 5: The spectrum distortion (N^{osc}/N^{SSM}) at Super-Kamiokande (upper panel) and SNO (lower panel) for different values of the mass ratio R_Δ and for the sterile-active mixing $\sin^2 2\alpha = 10^{-3}$. The solid lines correspond to the pure LMA case (no sterile neutrino). Normalization of spectra have been chosen to minimize χ^2 fit of spectrum for each case. We show also the Super-Kamiokande and SNO experimental data points with statistical errors only.